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DESIGNING SHIPS TO THE NATURAL ENVIRONMENT

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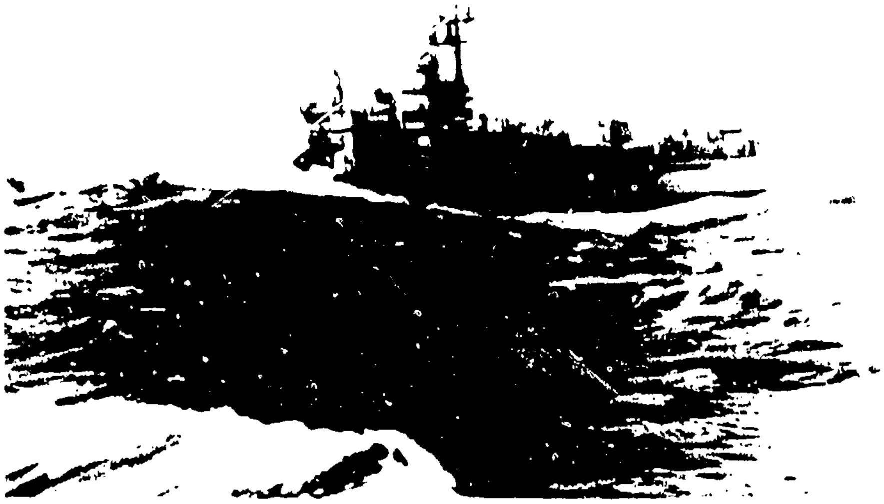

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ABSTRACT

Until recently, the natural environment has played a very minor role in ship design. The consideration of ship performance in the prevailing environment was focused primarily on optimization of calm water resistance and other factors related to the ship's propulsion system. During the 1970's, the Navy recognized the need to "design in" better ship performance and initiated the R&D efforts necessary to establish a technology base for doing so.

This paper outlines the state-of-the-art for environmental (primarily wave) modelling in the emerging seakeeping performance oriented design procedures. The sensitivity of the ship system to the environment is briefly examined. A standard procedure for specifying wave and wind conditions for ship design is recommended. Revision of U.S. Navy applied Sea State numeral definitions is discussed. A standard for specifying Sea State occurrences is offered as a new design tool.

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DEFINITIONS

CCA	Combatant Capability Assessment
Fully-Developed	A seaway which can grow no further regardless of wind duration
Modal Wave Period	The wave period associated with the peak energy of the density wave spectrum
Significant Wave Height	The wave height associated with the average of the one-third highest crest-to-trough waves in a wave record.
SS	Sea State
TLR	Top Level Requirement

INTRODUCTION

Remarkable as it may seem, until the 1970's, the U.S. Navy rarely considered the natural environment in the design of its surface ships. Even more remarkable is the fact that no ships have been lost due to excessive environmental loadings since Admiral Halsey's flotilla encountered the catastrophic typhoon of 1944 in the Western Pacific, see Reference 1. While one might argue that such losses just couldn't occur during peacetime operations, it is true that even in peacetime, millions of dollars a year are expended for ship and aircraft repairs caused by excessive wave and wind loadings, see Reference 2.

Over the years, naval hull forms have been designed primarily for calm water performance, e.g., by optimization of calm water ship resistance and other factors related to the ship's propulsion system. However, in the 1970's, it became clear that often our ships just could not keep up with those of our adversaries or even our allies in moderate to heavy weather conditions. In the early 1970's, CAPT J.W. Kehoe alerted us to our poor performance with a comparison of U.S. and U.S.S.R destroyer seakeeping behavior, see Reference 3:

"IN 1967, WHILE STEAMING IN HEAVY WEATHER INTO HEAD SEAS, THE COMMANDER OF A U.S. NAVY DESTROYER SQUADRON IN THE MEDITERRANEAN NOTED HIS DD-445, DD-682, AND DD-710 CLASS DESTROYERS TAKING SOLID GREEN WATER OVER THE BOW AND VERY HEAVY SPRAY ON THE BRIDGE. THE SOVIET KOTLIN-CLASS DESTROYER OPERATING IN CLOSE PROXIMITY TO THE CARRIER TASK GROUP APPEARED TO BE TAKING NO WATER OVER THE BOW AND ONLY OCCASIONALLY RAISED SPRAY ABOVE THE FO'C'S'LE DECK EDGE. U.S. SAILORS WORE FOUL WEATHER GEAR AND STAYED OFF THE FO'C'S'LE; SOVIET SAILORS PARADED ON THE FO'C'S'LE IN THEIR SHIRTSLEEVES."

Figure 1 illustrates the conditions which Kehoe describes. In 1975, VADM R.E. Adamson, Jr., then Commander, Naval Surface Forces Atlantic (COMNAVSURFLANT), stressed the gravity of the problem at the Seakeeping Workshop held at the U.S. Naval Academy, see Reference 4:

"SEAKEEPING, AS IT PERTAINS TO THE U.S. NAVY, IS THE ABILITY OF OUR SHIPS TO GO TO SEA, AND SUCCESSFULLY AND SAFELY EXECUTE THEIR MISSION DESPITE ADVERSE ENVIRONMENTAL FACTORS.

AS WE KNOW, A SHIP IS MORE THAN JUST A PLATFORM WITH EQUIPMENT. IT IS HER PEOPLE, OUR SAILORS, WHO WILL IN NO SMALL MEASURE DETERMINE THE SUCCESS OR FAILURE OF THE SHIP'S MISSION. I USED THE TERM "ADVERSE ENVIRONMENTAL FACTORS". IN THIS CONNECTION I REALIZE ONLY TOO WELL THAT THERE ARE LIMITS AS TO HOW FAR WE CAN OR SHOULD GO IN DESIGNING A SHIP SO AS TO COPE WITH THE ENVIRONMENT. FOR EXAMPLE, I COULD NOT EXPECT A SHIP TO BE ONE HUNDRED PERCENT READY WHILE SHE IS CAUGHT IN A TYPHOON OR HURRICANE.

NOW LET ME GIVE YOU A RECENT EXAMPLE OF HOW "SEAKEEPING" ABILITY HAS AFFECTED OUR SHIPS. ON A FLEET EXERCISE CONDUCTED SEVERAL MONTHS AGO, OUR SHIPS WERE SIMPLY NO MATCH AGAINST THE SEA AND WINDS FOR WHICH THE NORTH ATLANTIC IS NOTORIOUS. OUR COMMANDERS AND COMMANDING OFFICERS WERE FORCED TO FOREGO MANY OF THE OBJECTIVES OF THE EXERCISE IN ORDER TO ACCOMMODATE TO THE WEATHER. IN SOME CASES:

OUR SHIPS WERE FORCED TO SLOW TO PREVENT OR LESSEN THE IMPACT OF DAMAGE,
EXERCISES WERE CANCELLED,
WE COULD NOT REFUEL OUR SHIPS,
EQUIPMENT WAS DAMAGED AND
PERSONNEL WERE INJURED.

HOWEVER, SEVERAL SOVIET WARSHIPS WHICH WERE IN COMPANY AS OBSERVERS DID NOT APPEAR TO SUFFER THE SAME DEGREE OF DEGRADATION WE DID. THEY STEAMED SMARTLY AHEAD AND APPARENTLY WITHOUT DIFFICULTY. FURTHERMORE, IT WAS FOUND THAT WE SIMPLY DO NOT FARE AS WELL REGARDING THE SEAKEEPING ABILITY OF OUR SHIPS WHEN COMPARED TO SHIPS OF OUR ALLIES.

GOING TO SEA IS AN ADVENTURE. HOWEVER, WE ARE, IN ESSENCE, ASKING OUR SAILORS TO BATTLE NOT ONLY A POTENTIAL ENEMY THREAT ON THE SEAS, BUT THE SEAS THEMSELVES.

WE MUST DO BETTER. WITH OUR NAVY DOWN TO ITS PRESENT RELATIVELY LEAN (VERY LEAN) SIZE, THE SHIPS WE INTRODUCE FOR THE FUTURE MUST HAVE EVERY TECHNOLOGICAL EDGE POSSIBLE IN ORDER TO ENSURE THE SUCCESS OF THAT SHIP'S MISSION. OUR ERST-WHILE FOES SEEM TO BE DOING RATHER WELL. I CERTAINLY HOPE WE WILL DO BETTER."

As a result of this focus, several options to remedy the situation were identified:

1. Improve ship design through performance assessment (e.g., translate mission requirements into seakeeping performance requirements, integrate assessment technology into the design process for all ship types, and improve/develop combatant capability assessment (CCA) technology).

2. Improve environmental support to the fleet (e.g., onboard instrumentation, global and nested area long term forecasting, climatology, and operational guidance (identify ship behavior and mission sensitivity to the prevailing environment)).

3. Adopt novel or advanced ship types.

4. Adopt larger conventional ships.

5. Adopt optimum hull forms (e.g., synthesis of best hull geometry for both seakeeping and resistance).

Continuing research and development have permitted most of these options to impact recent ship designs. The progress is largely due to several exploratory development programs administered by the Naval Sea Systems Command and executed by the David W. Taylor Naval Ship R&D Center. This paper summarizes the results of some of the efforts aimed at developing the first option, i.e., improved ship design through performance assessment. In

particular, the state-of-the-art for modelling the environment for naval ship performance assessment is outlined. The utilization of Sea State descriptors is discussed and percent frequencies of occurrence for the North Atlantic and North Pacific are introduced. A Sea State chart applicable to the open ocean Northern Hemisphere is offered as a design standard.

SHIP PERFORMANCE ASSESSMENT

Before proceeding, a few words must be said about the requirement for environmental data in ship design.

Naval ships must survive and withstand two environmental forcing functions in order to accomplish their missions. These environmental loadings consist of the man-induced threat and the prevailing natural environment factors which influence the ship's activity and performance.

Ship performance assessment methodology has evolved substantially in the past seven years and is depicted in Figure 2. The methodology permits the ship designer to address specific requirements such as those illustrated in the Top Level Requirement (TLR) of Table 1. For example, for the given ship configuration and specified environment, ship responses (e.g., roll angle) are predicted using standard techniques, see Reference 5. If they exceed the given criterion (such as 5 degrees for operation of embarked helicopters), then the operability in that condition is considered degraded. In short, mission requirements are translated into seakeeping performance requirements. The natural environment must be specified here in order to define the total operating environment.

An example of a recent effort to compare the relative ability of a variety of notional and real ship designs to operate aircraft is given in Figure 3, from Reference 6. The results indicate degraded operability in Sea States 4, 5, and 6 for some ships for Vertical Take-Off and Landing (VTOL) operations.

Other examples of performance assessment are found throughout the literature, and a methodology review is provided in Reference 7. Clearly, performance assessment results are only as reliable as the input sets defined in Figure 2. The deficiencies of these sets are addressed in Reference 4, and hence will not be restated here. The research undertaken since 1975 to improve the natural environment inputs is described in internal Navy program planning documents. Specific results of recent Navy environmental research and development efforts are found in References 8 to 16.

SHIP SENSITIVITY TO THE NATURAL ENVIRONMENT

Table 2, from Reference 9, defines probable environmental factors which degrade ship performance. The table can be simplified, however. In short, it is hypothesized that the three most important surface environmental degraders to naval systems are:

1. Waves
2. Winds
3. Precipitation (rain)

Waves

Surface(d) ships are degraded by the combined effects of wave height, wave period (or length), and wave direction. Taken together, these three variables describe a Sea State. Greater ship performance degradation in lower Sea States can occur depending upon the combination of height, period, and directional properties. In general, the designer requires the following resolution for both sea (local wind driven) and swell (from decaying local winds or distant storms) waves:

1. Height - $\pm$ 0.3 meter (1 foot) of significant wave height

2. Period - $\pm$ 1 second of modal wave period for at least the corresponding range of wave lengths of 0.75 to 1.25 of the ship length

3. Direction - $\pm$ 7.5 degrees for each frequency (or period) component of the seaway.

Winds

Wind loadings on surface ships can introduce drift forces which retard stationkeeping functions. Like waves, winds also introduce structural damage to topside equipments. While a modelling capability in this area is clearly desirable, one does not exist except for higher altitudes than are pertinent to the ship structure. In fact, the only existing near surface wind models have been developed for civil engineering applications over land (e.g., skyscraper design). The resolution required for a marine model is unknown, except, of a course, that small scal· gustiness factors should be included.

Rain

Clearly, rain degrades sensors and other systems. For most combatant capability assessments, a rain drop size of about 2 mm is assumed.

Most of the remainder of this paper is focused on wave environment modelling which is certainly the single most important environmental degrader (excluding fouling) of ship hull performance.

STATE-OF-THE-ART IN WAVE MODELS

Wave modelling is described in detail in Reference 14. The reference provides a standard for conducting comparisons of predicted performance of NATO ships. It outlines current U.S. Navy practice and contains a data base of seasonal wave and wind statistics for NATO waters. The state-of-the-art in wave modelling in the U.S. Navy is described in such sufficient detail in Reference 14 that it is only briefly stated here.

Open Ocean Spectra

Bretschneider two-parameter wave spectra are employed. The spectra are defined by the two parameters significant wave height and modal wave period. For operationally average values, the spectra are treated with a cosine squared spreading function about $\pm$ 90 degrees. This produces a spectrum representative of short-crested seas. Otherwise, worst case or long-crested spectra are retained. Only unimodal seas are modelled.

Fetch-Limited, Coastal, or Shallow Water Spectra

A modified JONSWAP spectrum is employed. It too is defined by significant wave height and modal wave period. Generally, only long-crested seas are considered, though, there is some suggestion that higher-ordered cosine functions may provide good directional representation, see Reference 16.

Model

For many U.S. Navy design support evaluations, e.g., to address TLR's, the following steps provide sufficient wave inputs:

1. Determine Sea State(s) in which missions must be performed with some degree of success

2. Identify significant wave height and modal wave period pairs associated with those Sea States

3. Develop either Bretschneider or JONSWAP wave spectra using the wave height and wave period pairs (long- or short-crested) for implementation in the methodology outlined in Figure 2.

4. Develop percent times of operation by application of the percent frequencies of occurrence of the wave height and period pairs (Figure 3 was thusly developed).

An important feature here is that the first step really drives all of the rest. The initial specification of Sea State has the most important impact on the prediction of seakeeping performance. It is recognized that the use of Sea State numeral tables is a widespread practice employed by operators to describe wave and wind conditions. It is also recognized that many different tables are in use by naval, government, and maritime organizations throughout the world. This can lead to misunderstanding and poor communication, see Reference 17. A nationally, if not internationally, recognized standard is clearly required.

SEA STATE DEFINITIONS

In the early nineteenth century Admiral Beaufort of the British Navy invented a system for estimating and reporting wind speeds, see Reference 18. The system was originally based on the effects of various wind speeds on the

amount of canvas that a full-rigged frigate of the period could carry. It has since been modified, see Table 3 from Reference 19, and equates Beaufort force (or number) and wind speed to the state of the sea. Even in this century, shipboard observers have used the table to estimate wind speeds (e.g., ships without wind measuring devices). Table 3 includes a Sea State numeral definition still in worldwide use today. In fact, the World Meteorological Organization (WMO) has endorsed this definition as an international standard.

However, it is noted that for some decades, the U.S. Navy has utilized a Sea State definition based upon the relationships between wind speed and significant wave height for fully-developed seas, see Tables 4. Table 4 was developed by Wilbur Marks using the Neumann wind/wave relationship. The Neumann wind speed versus wave height relationship assumes the winds to be averaged at 7.5 m above the surface. This wind/wave relationship was superceeded by the Pierson-Moskowitz formulation in the late 1950's and Table 4 was thence modified for higher Sea States.

During a recent survey of NATO nations with regard to environmental modelling, it became clear that most nations have adopted the WMO standard. Therefore it was utilized in some recent U.S. Navy work, see Reference 15, which provides a data base of wave and wind conditions for NATO waters. Further inquiry, e.g., Reference 20, led to the observation that U.S. Navy operators also use the WMO standard and to the conclusion that the U.S. Navy design and research communities are probably the sole remaining users of Table 4 (or its modified version for higher-Sea States). Consideration of a change of practice is suggested.

Table 5 and Figure 4 provide comparisons of the old (Pierson-Moskowitz based) and new (WMO) Sea State numeral definitions. Figure 4 also compares the mean significant wave height values at each Sea State for each definition. Frequently, TLR's indicate required performance for Sea States 4, 5, and 6, see Table 1. Fortunately, the variation between the definitions of these three is not very substantial, see Figure 4. However, the older definition indicates higher wave heights for both lower and higher Sea States.

In general, the initial definition of required performance for a new ship design is in terms of Sea State. Thus the importance of Sea State definition is in the identification of significant wave heights for which seakeeping performance is assessed. The older definition of Sea State potentially permits the overprediction of performance degradation in lower and higher Sea States. Generally, Sea States below State 4 are considered unimportant to performance so the former is not significant. However, the later implies overprediction of failures in heavy weather. Generally, only limited capability is expected in Sea States 7 and above, see Table 1.

Considering that the impact upon current design practice is not substantial, it is recommended that the new (WMO) Sea State definition be adopted by the U.S. Navy design and research communities. This permits much more effective communication with our operators and with other NATO nations.

SEA STATE STANDARD

Table 6 provides annual percentage probabilities of occurrence for each Sea State in the North Atlantic. It also identifies associated modal wave period ranges. The table was developed using hindcasting techniques described elsewhere, see Reference 14. Table 7 provides similar data for the North Pacific. It was also developed using hindcasting techniques.

Figure 5 provides a comparison of the Sea Sate occurrences in the two basins. Clearly, the North Pacific is a more hostile operating region. If the exceedances for the two are averaged (treating basin size as negligible), the occurrences associated with the open ocean Northern Hemisphere result.

Figure 6 provides a comparison of the modal wave periods associated with each Sea State. Generally, the North Pacific provides a richer (broader) range of periods and they tend to be somewhat longer than those in the North Atlantic, which is probably due to the greater fetch. However, for Sea States 7 and above, somewhat longer wave periods are noted in the North Atlantic. The reason for this is unclear and warrants further investigation.

Figure 7 compares the most probable modal wave period for each Sea State and basin. The most probable modal wave period is frequently used in association with the mean significant wave height of the Sea State (e.g., as was the case in Figure 3 and as described in Table 1). A faired line through the data points provides a Sea State versus most probable modal wave period for the Northern Hemisphere. Figure 8, derived from Figure 6, provides an estimated summary of the modal wave period ranges for the Hemisphe .

Table 8 provides a complete summary of estimated Sea State occurrences for the Northern Hemisphere. The table is recommended for generic application to ship design problems. It provides the only known (to this author) large area Sea State occurrence data. The table provides useful data for TLR definition and together with specific percentage frequencies of occurrences of modal wave period, can be applied in all of the available naval seakeeping performance assessment methodologies. The table replaces a previous one, based solely on the North Atlantic and Sea State numerals of dubious universal acceptance.

SUMMARY

Table 8 is recommended as a design standard for specifying open ocean wave conditions in the Northern Hemisphere.

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Performance Requirements	Environmental Conditions *	Max. Roll Angle Allowed
• Operation of Embarked Helicopters	• Sea State 5 (Significant Wave Height 10.2 Feet, Wind Velocity 20 Knots) Ship Takes Best Heading for Lamps Helicopters.	5°
• Replenish and Strikedown Underway	• Sea State 5 (Significant Wave Height 10.2 Feet, Wind Velocity 20 Knots) Ship Takes Best Heading.	4°
• Continuous Efficient Operation/Without Significant Degradation (Other Than Replenishment and Operation of Embarked Helicopters)	• Sea State 6 (Significant Wave Height 16.9 Feet, Wind Velocity 30 Knots) All Ship Headings.	8° - 10°
• Limited Operation and Capability of Continuing its Mission Without Returning to Port for Repairs After Sea Subsides	• Sea State 7 (Significant Wave Height 30.6 Feet, Wind Velocity 44 Knots) Ship Takes Best Heading.	15°
• Survivability Without Serious Damage to Mission-Essential Subsystems	• Sea State 8 and Above (Significant Wave Height 51 Feet or Greater, Wind Velocity, 63 Knots or Greater) Ship Takes Best Heading.	N/A

*Using Old Sea State Numeral Definitions (e.g. See Figure 4 and Table 5.)

TABLE 1
TYPICAL TOP LEVEL REQUIREMENT (TLR)

	Speed	Maneuverability	Detection and Communication Systems (Radar, Helo, etc.)	Defense (Weapons)	Ship Tactics*
Sea Surface Wave height, period, direction (currents)	x	x		x	x
Surface Winds Wind speed, direction	x	x		x	x
Visibility			x	x	x
Cloud Cover			x	x	x
Ceiling Height			x		x
Precipitation			x	x	x
Fog			x	x	x
Humidity			x	x	x
Temperature			x		x
Sea Level Pressure			x		x
Storm	x	x	x	x	x
Ice Concentration	x	x			x
Superstructure Icing	x	x	x	x	x
Refractivity Profile			x		x
Ducting			x		x
Ionispheric Data			x		x

*Nominally, ship tactical decisions can be influenced by any environmental parameter which impacts any ship function.

TABLE 2
NATURAL ENVIRONMENT VERSUS SHIP FUNCTION

BEAUFORT WIND SCALE
WITH CORRESPONDING SEA STATE CODES

Beaufort number or force	Wind speed: knots	Wind speed: mph	Wind speed: meters per second	Wind speed: km per hour	World Meteorological Organization (1964)	Estimating wind speed: Effects observed far from land	Estimating wind speed: Effects observed near coast	Estimating wind speed: Effects observed on land	Sea State: Term and height of waves, in meters	Sea State: Code
0	under 1	under 1	0.0-0.2	under 1	Calm	Sea like mirror.	Calm.	Calm, smoke rises vertically.	Calm, glassy, 0	0
1	1-3	1-3	0.3-1.5	1-5	Light air	Ripples with appearance of scales; no foam crests.	Fishing smack just has steerage way.	Smoke drift indicates wind direction; vanes do not move.		
2	4-6	4-7	1.6-3.3	6-11	Light breeze	Small wavelets, crests of glassy appearance, not breaking.	Wind fills the sails of smacks which then travel at about 1-2 miles per hour.	Wind felt on face; leaves rustle; vanes begin to move.	Calm, rippled, 0-0.1	1
3	7-10	8-12	3.4-5.4	12-19	Gentle breeze	Large wavelets, crests begin to break, scattered whitecaps.	Smacks begin to careen and travel about 3-4 miles per hour.	Leaves, small twigs in constant motion; light flags extended.	Smooth, wavelets, 0.1-0.5	2
4	11-16	13-18	5.5-7.9	20-28	Moderate breeze	Small waves, becoming longer, numerous whitecaps.	Good working breeze, smacks carry all canvas with good list.	Dust, leaves, and loose paper raised up; small branches move.	Slight, 0.5-1.25	3
5	17-21	19-24	8.0-10.7	29-38	Fresh breeze	Moderate waves, taking longer form, many whitecaps; some spray.	Smacks shorten sail.	Small trees in leaf begin to sway.	Moderate, 1.25-2.5	4
6	22-27	25-31	10.8-13.8	39-49	Strong breeze	Larger waves forming; whitecaps everywhere; more spray.	Smacks have doubled reef in mainsail, care required when fishing.	Larger branches of trees in motion; whistling heard in wires.	Rough, 2.5-4	5
7	28-33	32-38	13.9-17.1	50-61	Near gale	Sea heaps up; white foam from breaking waves begins to be blown in streaks.	Smacks remain in harbor and those at sea lie-to.	Whole trees in motion; resistance felt in walking against wind.	Very rough, 4-6	6
8	34-40	39-46	17.2-20.7	62-74	Gale	Moderately high waves of greater length, edges of crests begin to break into spindrift, foam is blown in well-marked streaks.	All smacks make for harbor, if near.	Twigs and small branches broken off trees; progress generally impeded.		
9	41-47	47-54	20.8-24.4	75-88	Strong gale	High waves, sea begins to roll, dense streaks of foam; spray may reduce visibility.		Slight structural damage occurs; slate blown from roofs.		
10	48-55	55-63	24.5-28.4	89-102	Storm	Very high waves with overhanging crests; sea takes white appearance as foam is blown in very dense streaks; rolling is heavy and visibility reduced.		Seldom experienced on land; trees broken or uprooted; considerable structural damage occurs.	High, 6-9	7
11	56-63	64-72	28.5-32.6	103-117	Violent storm	Exceptionally high waves; sea covered with white foam patches; visibility still more reduced.		Very rarely experienced on land; usually accompanied by widespread damage.	Very high, 9-14	8
12	64 and over	73 and over	32.7 and over	118 and over	Hurricane	Air filled with foam; sea completely white with driving spray; visibility greatly reduced.			Phenomenal, over 14	9

Note: Since January 1, 1955, weather map symbols have been based upon wind speed in knots, at five-knot intervals, rather than upon Beaufort number.

TABLE 3
BEAUFORT WIND SCALE WITH CORRESPONDING SEA STATE CODES

WIND AND SEA SCALE FOR FULLY ARISEN SEA														
SEA-GENERAL		WIND[3]				SEA[3]								
						WAVE HEIGHT FEET								
SEA STATE[1]	DESCRIPTION[2]	(BEAUFORT) WIND FORCE	DESCRIPTION	RANGE (KNOTS)	WIND VELOCITY (KNOTS)	AVERAGE	SIGNIFICANT	AVERAGE $\frac{1}{10}$ HIGHEST	SIGNIFICANT RANGE OF PERIODS (SECONDS)	T_{max} (PERIOD OF MAXIMUM ENERGY OF SPECTRUM)	$\bar{T}$ (AVERAGE PERIOD)	$\bar{\lambda}$ (AVERAGE WAVE LENGTH)	MINIMUM FETCH (NAUTICAL MILES)	MINIMUM DURATION (HOURS)
0	Sea like a mirror.	0	Calm	Less than 1	a) 0	0	0	0	-	-	-	-	-	-
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light Airs	1 - 3	2	0.05	0.08	0.10	up to 1.2 sec	0.7	0.5	10 in.	5	18 min
1	Small wavelets, still short but more pronounced; crests have a glassy appearance, but do not break.	2	Light Breeze	4 - 6	5	0.18	0.29	0.37	0.4-2.8	2.0	1.4	6.7 ft	8	39 min
	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	3	Gentle Breeze	7 - 10	8.5	0.6	1.0	1.2	0.8-5.0	3.4	2.4	20	9.8	1.7 hrs
					10	0.88	1.4	1.8	1.0-6.0	4	2.9	27	10	2.4
2	Small waves, becoming larger; fairly frequent white horses.	4	Moderate Breeze	11-16	12	1.4	2.2	2.8	1.0-7.0	4.8	3.4	40	18	3.8
					13.5	1.8	2.9	3.7	1.4-7.6	5.4	3.9	52	24	4.8
3					14	2.0	3.3	4.2	1.5-7.8	5.6	4.0	59	28	5.2
					16	2.9	4.6	5.8	2.0-8.8	6.5	4.6	71	40	6.6
4	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray).	5	Fresh Breeze	17-21	18	3.8	6.1	7.8	2.5-10.0	7.2	5.1	90	55	8.3
					19	4.3	6.9	8.7	2.8-10.6	7.7	5.4	99	65	9.2
					20	5.0	8.0	10	3.0-11.1	8.1	5.7	111	75	10
5	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray).	6	Strong Breeze	22-27	22	6.4	10	13	3.4-12.2	8.9	6.3	134	100	12
					24	7.9	12	16	3.7-13.5	9.7	6.8	160	130	14
					24.5	8.2	13	17	3.8-13.6	9.9	7.0	164	140	15
6					26	9.6	15	20	4.0-14.5	10.5	7.4	188	180	17
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. (Spindrift begins to be seen).	7	Moderate Gale	28-33	28	11	18	23	4.5-15.5	11.3	7.9	212	230	20
					30	14	22	28	4.7-16.7	12.1	8.6	250	280	23
					30.5	14	23	29	4.8-17.0	12.4	8.7	258	290	24
					32	16	26	33	5.0-17.5	12.9	9.1	285	340	27
7	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	34-40	34	19	30	38	5.5-18.5	13.6	9.7	322	420	30
					36	21	35	44	5.8-19.7	14.5	10.3	363	500	34
					37	23	37	46.7	6-20.5	14.9	10.5	376	530	37
					38	25	40	50	6.2-20.8	15.4	10.7	392	600	38
					40	28	45	58	6.5-21.7	16.1	11.4	444	710	42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong Gale	41-47	42	31	50	64	7-23	17.0	12.0	492	830	47
					44	36	58	73	7-24.2	17.7	12.5	534	960	52
					46	40	64	81	7-25	18.6	13.1	590	1110	57
	Very high waves with long overhanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shocklike. Visibility is affected.	10	Whole Gale*	48-55	48	44	71	90	7.5-26	19.4	13.8	650	1250	63
					50	49	78	99	7.5-27	20.2	14.3	700	1420	69
					51.5	52	83	106	8-28.2	20.8	14.7	736	1560	73
9					52	54	87	110	8-28.5	21.0	14.8	750	1610	75
					54	59	95	121	8-29.5	21.8	15.4	810	1800	81
	Exceptionally high waves (Small and medium-sized ships might for a long time be lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11	Storm*	56-63	56	64	103	130	8.5-31	22.6	16.3	910	2100	88
					59.5	73	116	148	10-32	24	17.0	985	2500	101
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane*	64-71	> 64	> 80 b)	> 128 b)	> 164 b)	10-(35)	(26)	(18)	~	~	~

*For hurricane winds (and often whole gale and storm winds) required durations and fetches are rarely attained. Seas are therefore not fully arisen.

a) A heavy box around this value means that the values tabulated are at the center of the Beaufort range.

b) For such high winds, the seas are confused. The wave crests blow off, and the water and the air mix.

1) Encyclopedia of Nautical Knowledge, W.A. McEwen and A.H. Lewis, Cornell Maritime Press, Cambridge, Maryland 1953, p. 483

2) Manual of Seamanship, Volume II, Admiralty, London, H.M. Stationery Office, 1952, pp. 717-718

3) Practical Methods for observing and forecasting Ocean Waves, Pierson, Neumann, James, N.Y. Univ, College of Engin, 1953.

This table compiled by Wilbur Marks,
David Taylor Model Basin

TABLE 4
WAVE AND SEA SCALE FOR FULLY ARISEN SEAS (NEUMANN)

Sea State Number	SIGNIFICANT WAVE HEIGHT			
	METERS		FEET	
	Old	New	Old	New
0 - 1	0.0 - 0.6	0.0 - 0.1	0 - 1.9	0 - 0.3
2	0.6 - 1.3	0.1 - 0.5	1.9 - 4.1	.3 - 1.6
3	1.3 - 1.7	0.5 - 1.25	4.1 - 5.7	1.6 - 4.1
4	1.7 - 2.2	1.25 - 2.5	5.7 - 7.4	4.1 - 8.2
5	2.2 - 4.0	2.5 - 4.0	7.4 - 13.0	8.2 - 13.1
6	4.0 - 6.3	4.0 - 6.0	13.0 - 20.8	13.1 - 19.7
7	6.3 - 12.3	6.0 - 9.0	20.8 - 40.3	19.7 - 29.5
8	12.3 - 18.8	9.0 - 14.0	40.3 - 61.6	29.5 - 45.5
>8	>18.8	>14.0	>61.6	>45.5

TABLE 5
OLD (NEUMANN, PIERSON — MOSKOWITZ) VERSUS NEW (WMO) SEA STATE DEFINITIONS

Sea State Number	Significant Wave Height (m)		Sustained Wind Speed (Knots)*		Percentage Probability of Sea State	Modal Wave Period (Sec)	
	Range	Mean	Range	Mean		Range**	Most Probable***
0 - 1	0 - 0.1	0.05	0 - 6	3	0	—	—
2	0.1 - 0.5	0.3	7 - 10	8.5	7.2	3.3 - 12.8	7.5
3	0.5 - 1.25	0.88	11 - 16	13.5	22.4	5.0 - 14.8	7.5
4	1.25 - 2.5	1.88	17 - 21	19	28.7	6.1 - 15.2	8.8
5	2.5 - 4	3.25	22 - 27	24.5	15.5	8.3 - 15.5	9.7
6	4 - 6	5	28 - 47	37.5	18.7	9.8 - 16.2	12.4
7	6 - 9	7.5	48 - 55	51.5	6.1	11.8 - 18.5	15.0
8	9 - 14	11.5	56 - 63	59.5	1.2	14.2 - 18.6	16.4
>8	>14	>14	>63	>63	<0.05	18.0 - 23.7	20.0

*Ambient wind sustained at 19.5 m above surface to generate fully-developed seas. To convert to another altitude, H_2, apply $V_2 = V_1(H_2/19.5)^{1/7}$

**Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.

***Based on periods associated with central frequencies included in Hindcast Climatology.

TABLE 6
ANNUAL SEA STATE OCCURRENCES IN THE OPEN OCEAN
NORTH ATLANTIC

Sea State Number	Significant Wave Height (m)		Sustained Wind Speed (Knots)*		Percentage Probability of Sea State	Modal Wave Period (Sec)	
	Range	Mean	Range	Mean		Range**	Most Probable***
0 - 1	0 - 0.1	0.05	0 - 6	3	0	—	—
2	0.1 - 0.5	0.3	7 - 10	8.5	4.1	3.0 - 15.0	7.5
3	0.5 - 1.25	0.88	11 - 16	13.5	16.9	5.2 - 15.5	7.5
4	1.25 - 2.5	1.88	17 - 21	19	27.8	5.9 - 15.5	8.8
5	2.5 - 4	3.25	22 - 27	24.5	23.5	7.2 - 16.5	9.7
6	4 - 6	5	23 - 47	37.5	16.3	9.3 - 16.5	13.8
7	6 - 9	7.5	48 - 55	51.5	9.1	10.0 - 17.2	13.8
8	9 - 14	11.5	56 - 63	59.5	2.2	13.0 - 18.4	18.0
>8	>14	>14	>63	>63	0.1	20.0	20.0

*Ambient wind sustained at 19.5 m above surface to generate fully-developed seas. To convert to another altitude, H_2, apply $V_2 = V_1(H_2/19.5)^{1/7}$

**Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.

***Based on periods associated with central frequencies included in Hindcast Climatology.

TABLE 7
ANNUAL SEA STATE OCCURRENCES IN THE OPEN OCEAN
NORTH PACIFIC

Sea State Number	Significant Wave Height (m)		Sustained Wind Speed (Knots)*		Percentage Probability of Sea State	Modal Wave Period (Sec)	
	Range	Mean	Range	Mean		Range**	Most Probable
0 - 1	0 - 0.1	0.05	0 - 6	3	0	—	—
2	0.1 - 0.5	0.3	7 - 10	8.5	5.7	3 - 15	7
3	0.5 - 1.25	0.88	11 - 16	13.5	19.7	5 - 15.5	8
4	1.25 - 2.5	1.88	17 - 21	19	28.3	6 - 16	9
5	2.5 - 4	3.25	22 - 27	24.5	19.5	7 - 16.5	10
6	4 - 6	5	28 - 47	37.5	17.5	9 - 17	12
7	6 - 9	7.5	48 - 55	51.5	7.6	10 - 18	14
8	9 - 14	11.5	56 - 63	59.5	1.7	13 - 19	17
>8	>14	>14	>63	>63	0.1	18 - 24	20

*Ambient wind sustained at 19.5 m above surface to generate fully-developed seas. To convert to another altitude, H_2, apply $V_2 = V_1(H_2/19.5)^{1/7}$

**Minimum is 5 percentile and maximum is 95 percentile for periods given wave height range.

TABLE 8
ANNUAL SEA STATE OCCURRENCES IN THE OPEN OCEAN
NORTHERN HEMISPHERE

FIGURE 1

One Comparison of U.S. and Soviet Destroyer Seakeeping

Soviet Kotlin-class destroyer on right, U.S. 7?0 class on left

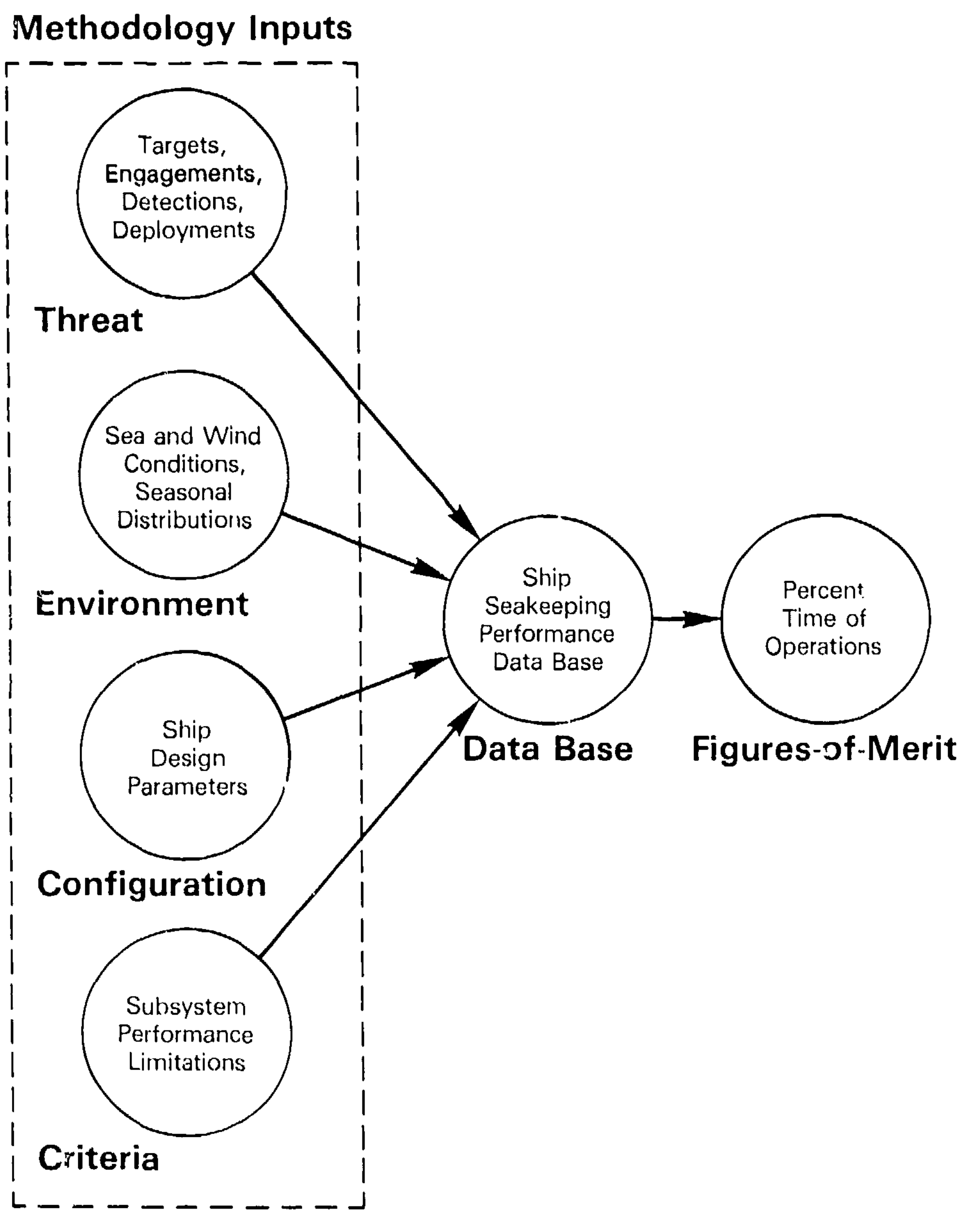

FIGURE 2
OUTLINE OF SEAKEEPING PERFORMANCE
ASSESSMENT METHODOLOGY

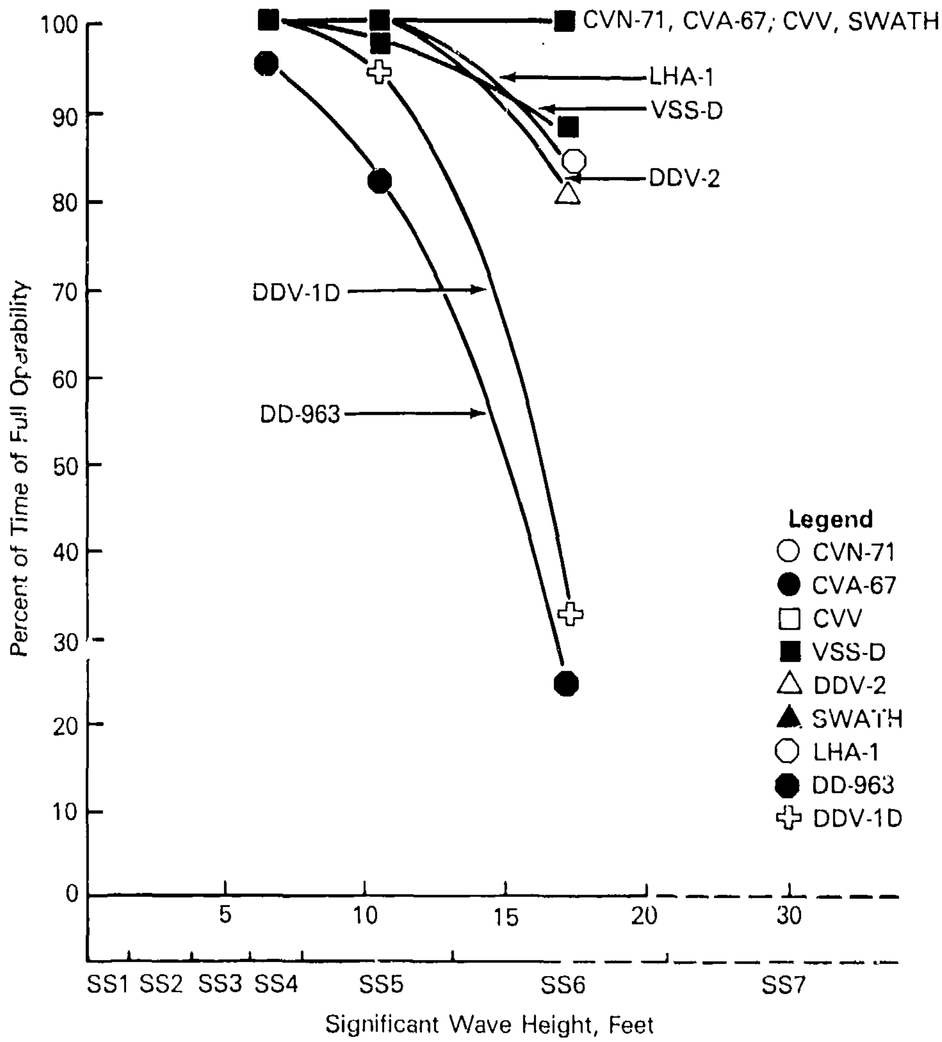

FIGURE 3
TYPICAL PERFORMANCE FIGURE OF MERIT
(COMPARISON OF SHIP VTO FUNCTIONAL CAPABILITY)

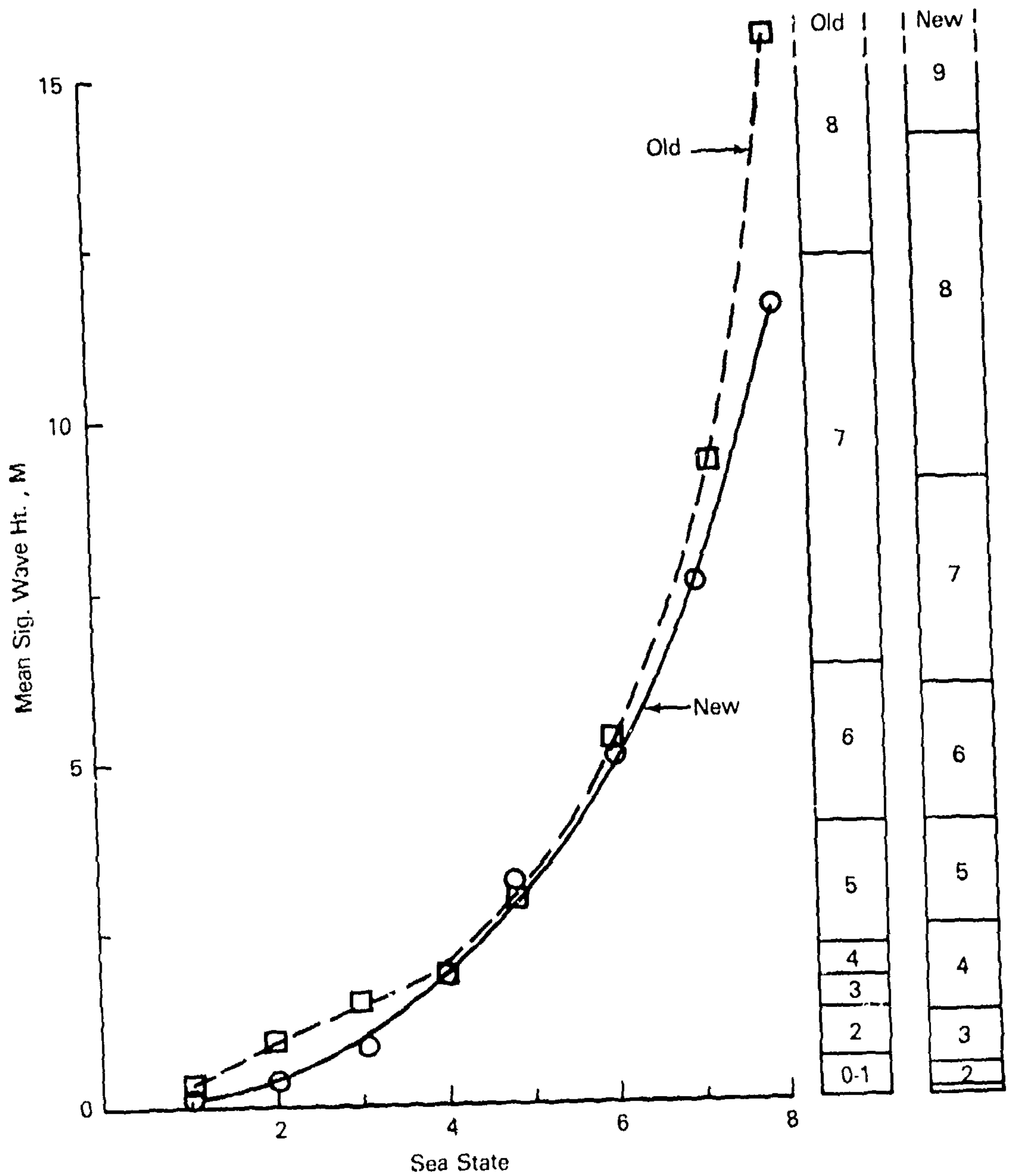

FIGURE 4
OLD (NEUMANN, PIERSON-MOSKOWITZ) VERSUS NEW (WMO) SEA STATE DEFINITIONS

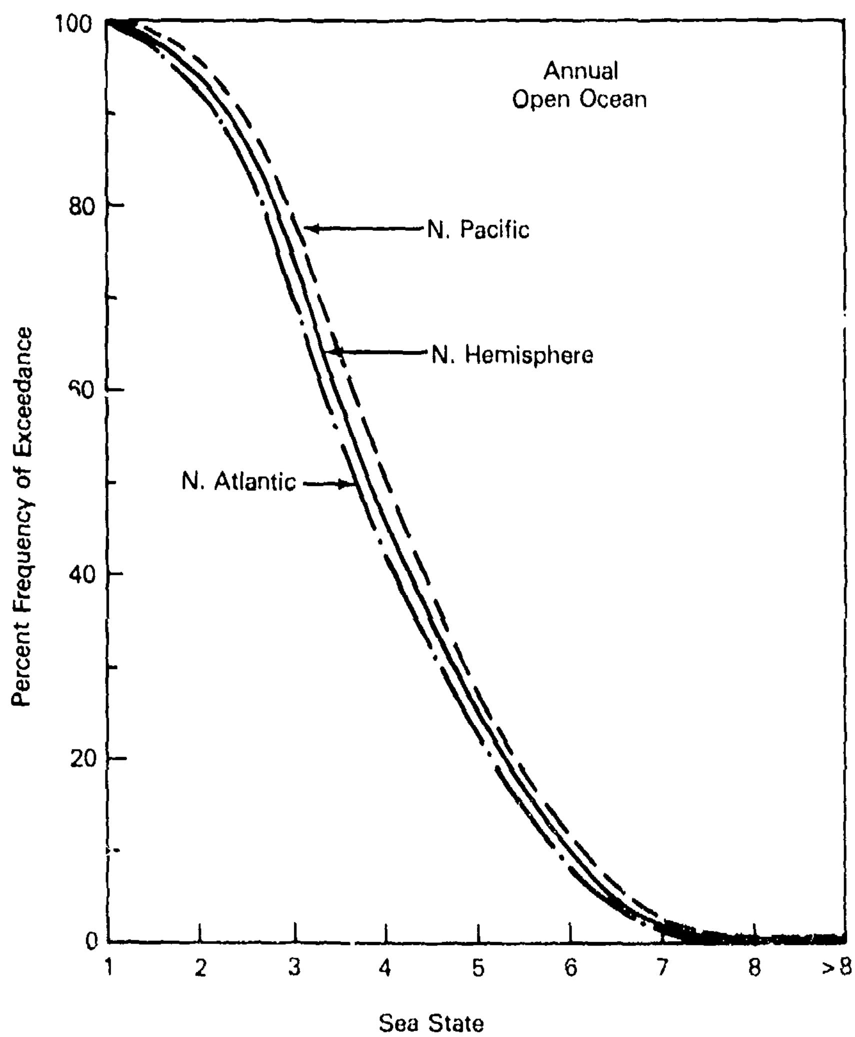

FIGURE 5
SEA STATE PERCENT FREQUENCIES OF EXCEEDANCE FOR THE NORTH ATLANTIC, NORTH PACIFIC, AND NORTHERN HEMISPHERE

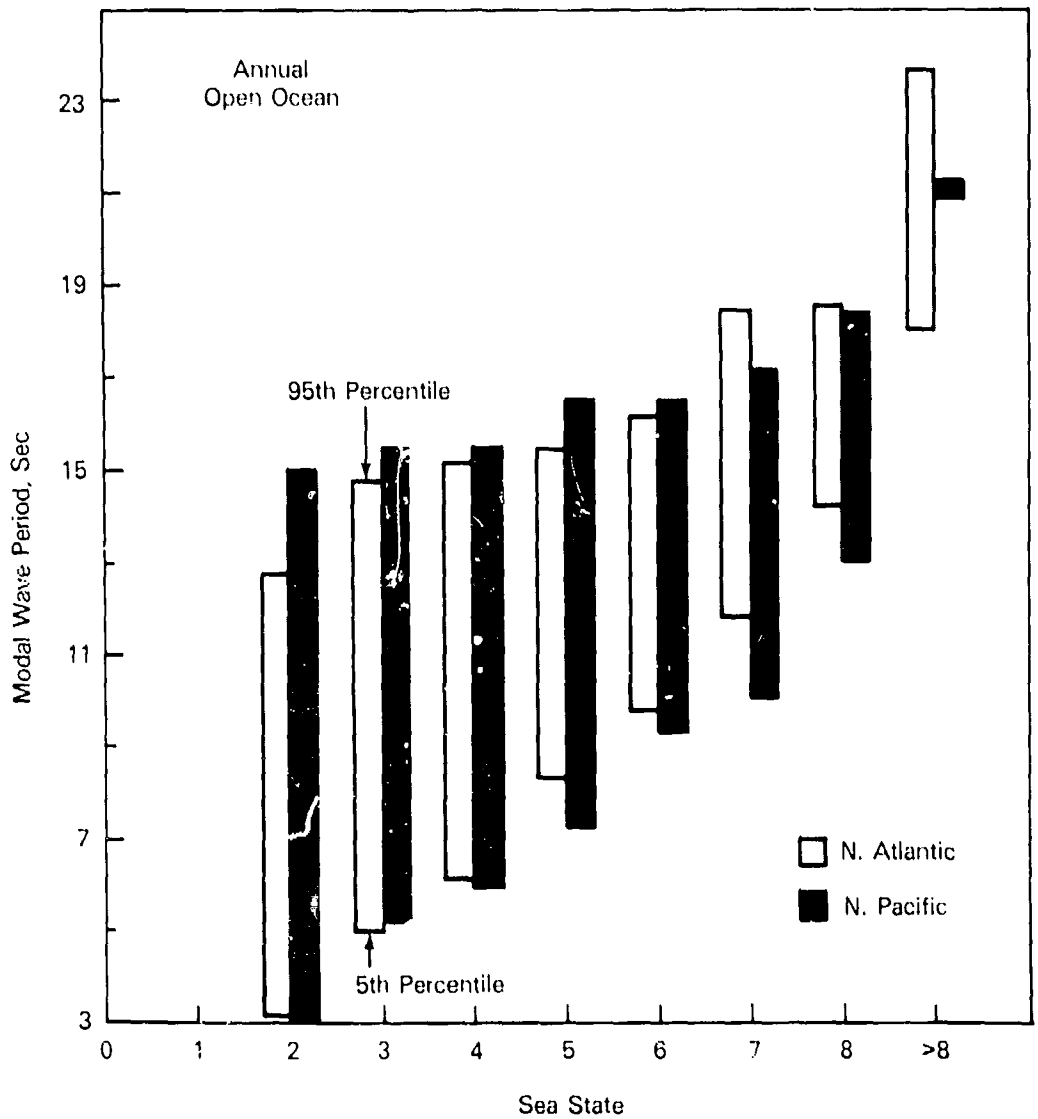

FIGURE 6
MODAL WAVE PERIOD RANGES VERSUS SEA STATE FOR THE NORTH ATLANTIC AND NORTH PACIFIC

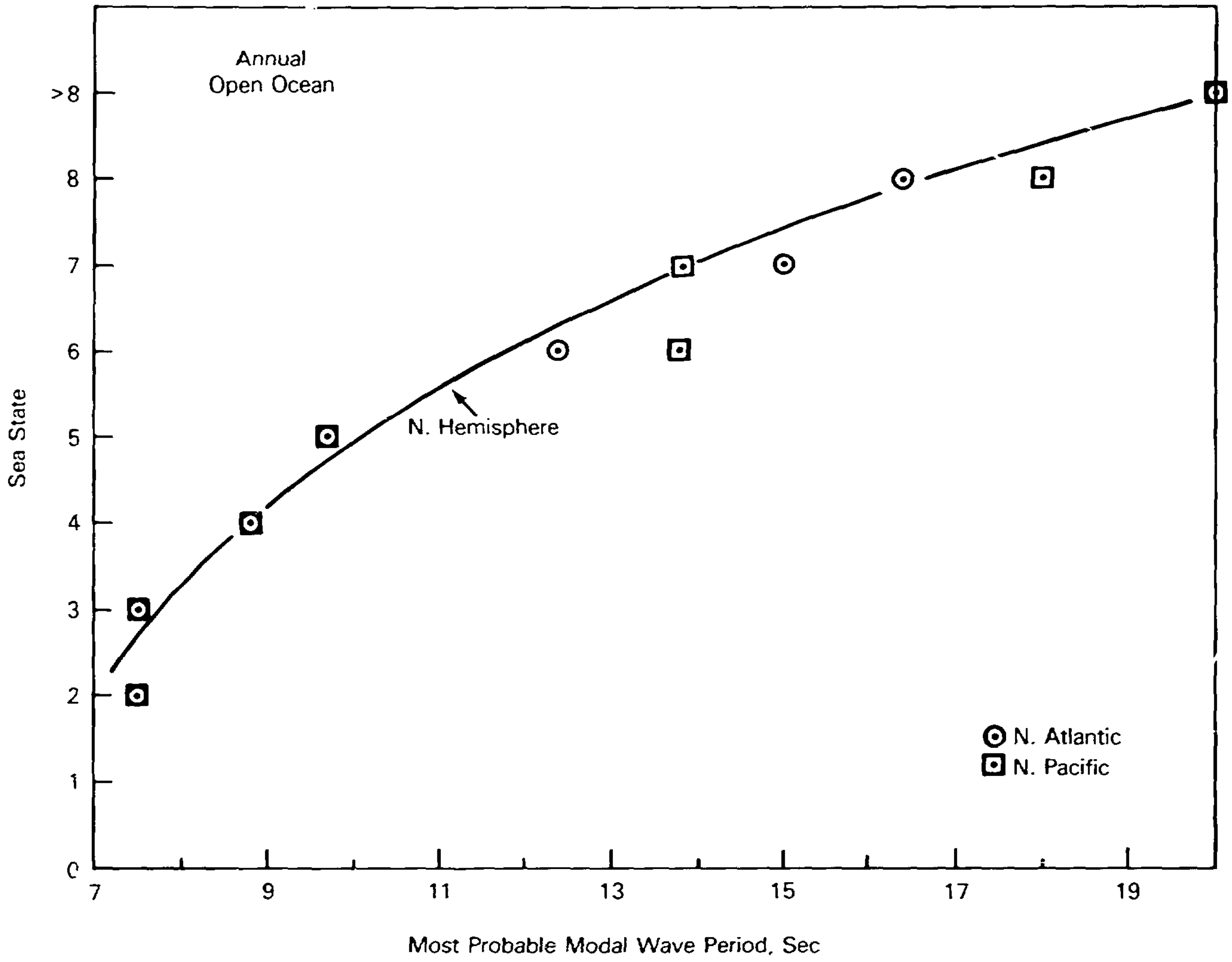

FIGURE 7
MOST PROBABLE MCDAL PERIODS VERSUS SEA STATE FOR THE NORTH ATLANTIC, NORTH PACIFIC AND NORTHERN HEMISPHERE

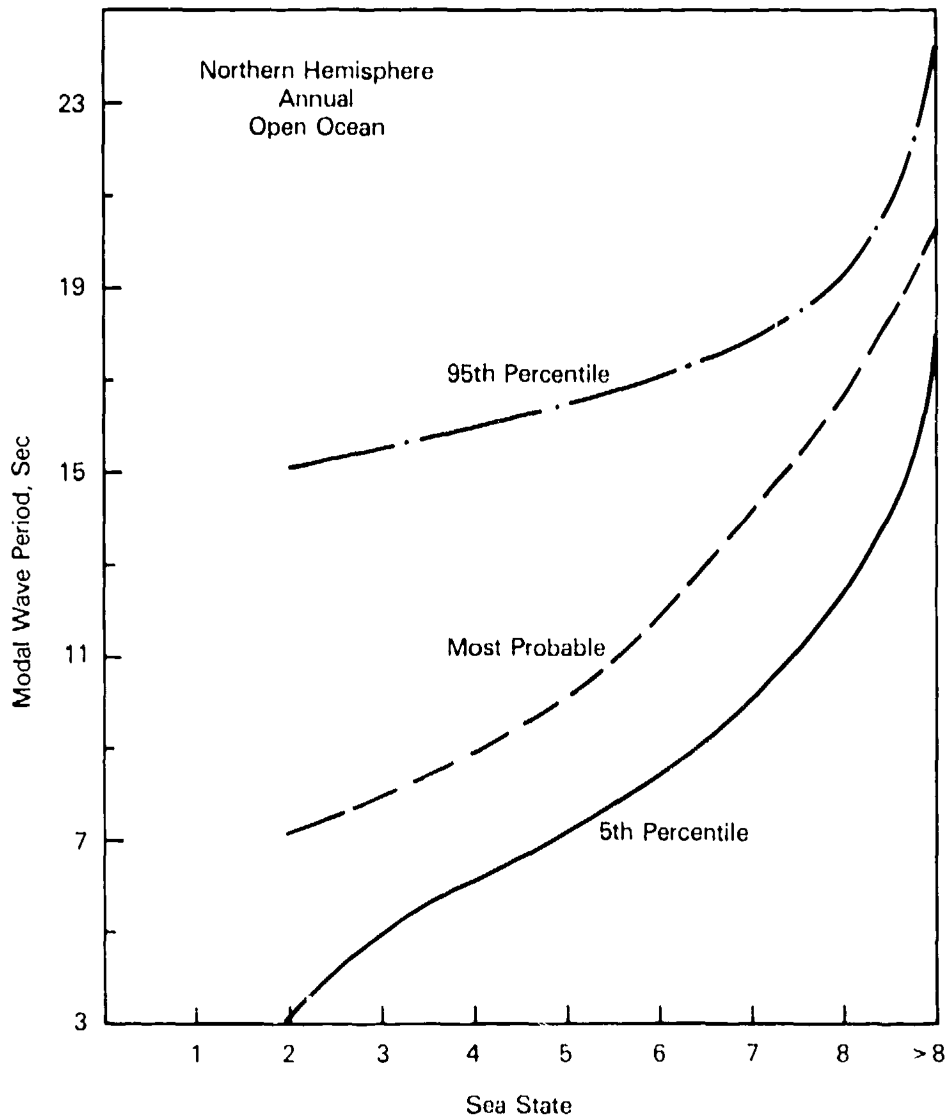

FIGURE 8
ESTIMATED MODAL WAVE PERIODS FOR THE NORTHERN HEMISPHERE